Creating Spin Currents in Silicon

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Semiconductor Spintronics: The electronics industry to date has relied upon the control of charge flow, combined with size scaling (i.e., reducing the physical size of elements such as transistors), to continuously increase the performance of existing electronics. This trend, widely known as Moore's Law, has been remarkably successful. However, size scaling cannot continue indefinitely as atomic length scales are reached (the "Moore's Law Roadblock"), so new approaches must be developed. Basic research efforts at NRL and elsewhere have shown that spin angular momentum, another fundamental property of the electron, can be used to store and process information in solid-state devices. Subsequently, the *International Technology Roadmap for Semiconductors*[1] has identified the electron's spin as a new state variable that should be explored for processing information in the fundamentally new ways that will be required beyond the ultimate scaling limits of silicon-based complementary metal-oxide-semiconductor (CMOS) technology. This approach is known as semiconductor spintronics.

The Challenge: Electrical injection and transport of spin-polarized carriers is prerequisite for developing such an approach. Although good results have been realized in III-V semiconductors such as gallium arsenide,[2] little progress has been made in silicon, despite its overwhelming dominance of the industry. This is because spin-polarized carriers can be readily created and probed by powerful optical spectroscopic techniques in direct-gap semiconductors (e.g., GaAs), but these techniques often fail or are very difficult to use in indirect-gap materials such as silicon. Thus the challenge is twofold: to develop a means to electrically inject spin-polarized carriers into silicon, and to develop a means to detect and quantify their behavior.

Spin Injection and Detection: To create spin-polarized carriers in silicon, we electrically inject them from a ferromagnetic metal contact, which naturally has more electrons with spin oriented in a particular direction determined by the magnetization ("spin-up" or "majority spin") than in the opposite direction ("spin-down" or "minority spin"). The spin polarization in a typical ferromagnetic metal is ~45%. A thin layer of aluminum oxide between an iron contact and the silicon serves as a tunnel barrier to facilitate

spin injection by controlling the series resistance and preventing interaction between the iron and the silicon, as shown in Fig. 9. To detect the presence of the spin-polarized electrons and assess the efficiency of injection, we design sample structures that allow the electrons to radiatively recombine. By conservation of momentum, the electrons' spin angular momentum is transferred to the photons, which we can detect, and an analysis of the polarization of the weak electroluminescence (EL) provides a direct measure of the initial electron spin polarization.

Figure 9 shows a band diagram of the contact region and the two types of samples studied.[3] First, Si *n-i-p* doped heterostructures were grown by molecular beam epitaxy (MBE) on *p*-doped Si(001) wafers. Second, Si epilayers (*n*-doped, 80 nm thick) were grown on *n*-$Al_{0.1}Ga_{0.9}As$/GaAs/*p*-$Al_{0.3}Ga_{0.7}As$ quantum well structures on *p*-GaAs(001) substrates. Although the crystalline quality of the Si is lower and an additional heterointerface is introduced (Si/$Al_{0.1}Ga_{0.9}As$), these latter samples emit strong EL from the direct-gap GaAs. This enables a quantitative determination of the spin polarization of the electrons which go through the Si and reach the GaAs via standard analysis using quantum selection rules.[2]

Surface-emitting light-emitting diode (LED) structures are fabricated from each sample type. Typical spectra from the Si *n-i-p* LEDs are shown in Fig. 10 at 50 K and 80 K (the EL is too weak at higher temperatures); electrons electrically injected from the iron radiatively recombine in the Si, with the dominant emission peak at 1.07 eV. At zero field (0 T), no circular polarization is observed because the Fe magnetization and corresponding electron spin orientation lie in-plane and orthogonal to the light propagation direction. Although spin injection may occur, it cannot be detected with this alignment. Thus, a magnetic field is applied to rotate the Fe spin orientation out-of-plane, and the spectral features then exhibit circular polarization, P_{circ}, as shown by the difference between the red (σ+) and blue (σ–) curves in the 3 T spectra.

The magnetic field dependence of P_{circ} for each feature is summarized in Fig. 11. As the Fe magnetization (and electron spin orientation) rotates out of plane with increasing field, P_{circ} increases and saturates. Note that for each feature, P_{circ} tracks the magnetization of the Fe contact, shown as a solid line scaled to the data, demonstrating that the spin orientation of the electrons that radiatively recombine in the Si originates with the spin polarization of the Fe contact. A rate equation analysis which includes the electrons' radiative and spin lifetimes shows that the net spin polarization of the electrons in the Si is 30%. The spin injection process is therefore relatively efficient, given that the initial spin polarization of the Fe is only 45%.

Support for this estimate is provided by data from the second type of sample which incorporates a GaAs quantum well, where the EL is much stronger and persists to 125 K. In these samples, electrons injected from the Fe into the Si drift across the $Si/Al_{0.1}Ga_{0.9}As$ interface with applied bias and radiatively recombine in the GaAs. Standard quantum selection rule analysis of the data determine that the GaAs electron spin polarization is 10%. This value is remarkably high and attests to the robust character of spin transport, given the large lattice mismatch of Si/GaAs, the additional air-exposed interface, and the band offsets involved.

Impact and Outlook: This approach injects spin-polarized electrons near the silicon conduction band edge with near unity conversion efficiency and low bias voltages (~2 eV) compatible with CMOS technology. The realization of efficient electrical injection and significant spin polarization using a simple magnetic tunnel barrier compatible with "back-end" silicon processing will greatly facilitate development of silicon-based spintronic devices.

[Sponsored by NRL]

References

[1] *International Technology Roadmap for Semiconductors*, 2007 Edition, pp. 30-43, http://www.itrs.net/reports.html.

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[3] B.T. Jonker, G. Kioseoglou, A.T. Hanbicki, C.H. Li, and P.E. Thompson, "Electrical Spin Injection into Silicon from a Ferromagnetic Metal/Tunnel Barrier Contact," *Nature Physics* **3**, 542 (2007). ★
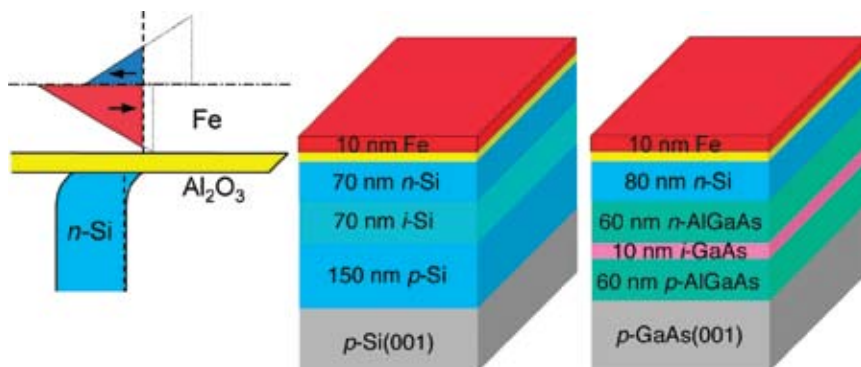
FIGURE 9
Band diagram of the $Fe/Al_2O_3/Si$ contact and cross section of the two types of samples studied.
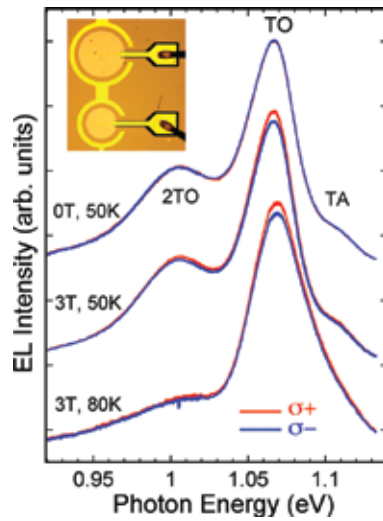
FIGURE 10
Electroluminescence spectra from the Si *n-i-p* structure with the Fe/Al2O3 contact at 50 K and 80 K, and at magnetic fields of 0 T and 3 T. The inset shows an optical photograph of the LEDs studied. Spectral peaks corresponding to transverse acoustic (TA) and transverse optical (TO) mediated recombination are identified in the figure.

FIGURE 11
Magnetic field dependence of P_{circ} for the spectral features shown in Fig. 10.